Report of the Supernova Working Group

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Activity to Date

- Had five meetings
  - Telecons April 1, April 12, April 29, May 6
  - Face to face today
- Jeff Kruk from the Project Office participated in all of these meetings. This was (and will continue to be) a useful liason with the Project Office
- Most of the work happening outside of these meetings
- Have set up a web site to faclitate this

Planned Activity

- In response to the "Primary Charge"

  All of the members of the working group are working together to develop the best supernova program for the Omega mission as defined for WFIRST. Some progress on this…
- In response to the "Secondary Charge"

  Some of us will look at alternative mission designs to improve performance or reduce costs or both . This will start in the next few weeks.

Supernova Survey with Omega as Defined for WFIRST

- Assume WFIRST as Omega Design with 1.5 m obstructed view (on axis) Telescope
- Plan on a “6 month” supernova survey that runs for two years making a 30 hour visit every 5 days (i.e.1/4 time for two years)
  - Type 1a rise time ~2 weeks, decay time ~6 weeks in SNe rest frame, twice this for SNe at redshift 1.0
  - Need to follow supernovae for about this period of time after discovery to obtain full lightcurves
  - Can not use supernova discovered within the last two or three months of a continuos survey time
  - End effects for short continuous survey times very severe

Mixed Imaging/Spectroscopic Survey

- Started out considering a survey with spectroscopy only
  - Use spectra to type supernovae, measure redshifts, and obtain precision lightcurves from spectrophotometry
  - Places no requirements on filters
  - Spectrometry with slitless prism spectrometer very slow due to high backgrounds
- We all agreed that a survey using both imaging and spectrometry is the way to go

Imaging/Spectroscopic Survey

- Split each 30 hour visit between imaging and spectroscopy
- Use imaging in many filters to obtain the lightcurves
- Use the spectra to determine that we have a Type 1a and to get the redshift (requires shorter exposure times compared to using spectra to get precision lightcurves)

Proposed Filter Bands for Imaging

- Set up 5 filter bands as follows, all with $\lambda/\Delta\lambda = 4.5$
- These are similar in spirit to the set mentioned by Paul

  (0.4-0.6, 0.6-0.85, 0.85-1.1, 1.1-1.4, 1.4-1.7)

  but shifted up by 0.2 or 0.3

Filter No	λ central	$\Delta\lambda$	Range
1	0.72	0.1600	0.60 to 0.80
2	0.90	0.2000	0.80 to 1.00
3	1.15	0.2556	1.02 to 1.28
4	1.45	0.3222	1.29 to 1.61
5	1.80	0.4000	1.60 to 2.00

A 3 Tiered Imaging/Spectroscopy Survey

Image each area in 3 filters but plan to use the bluer filters for the lower z SNe, redder filters for the higher redshift ones.

Z region	Area sqdeg	Z max	Exposure Time	Filters Used			
Low	9.00	0.5	200	1 – 2 - 3			
Mid	3.24	0.8	2400	2 – 3 - 4			
High	1.44	1.2	6000	3 – 4 - 5			

Translating Filter Bands to SNe Rest Frame

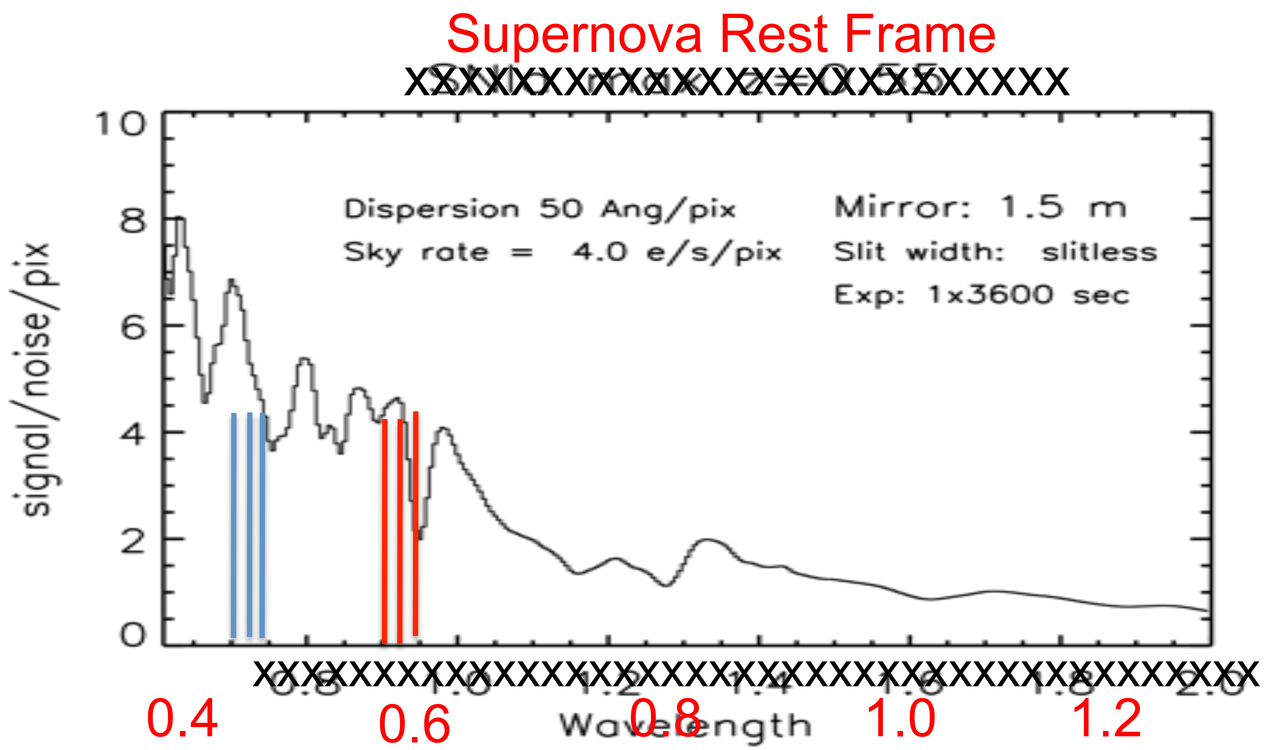
- Consider lightcurves in the bluest band at various redshifts
- Using 5 Filters, need a modest K correction

Supernova	Z	Bluest Filter	Rest Frame Band
SNE1	0.4	0.6 – 0.8	0.43 – 0.57
SNE2	0.8	0.8 – 1.0	0.44 -- 0.56
SNE3	1.2	1.0 – 1.28	0.45 – 0.58

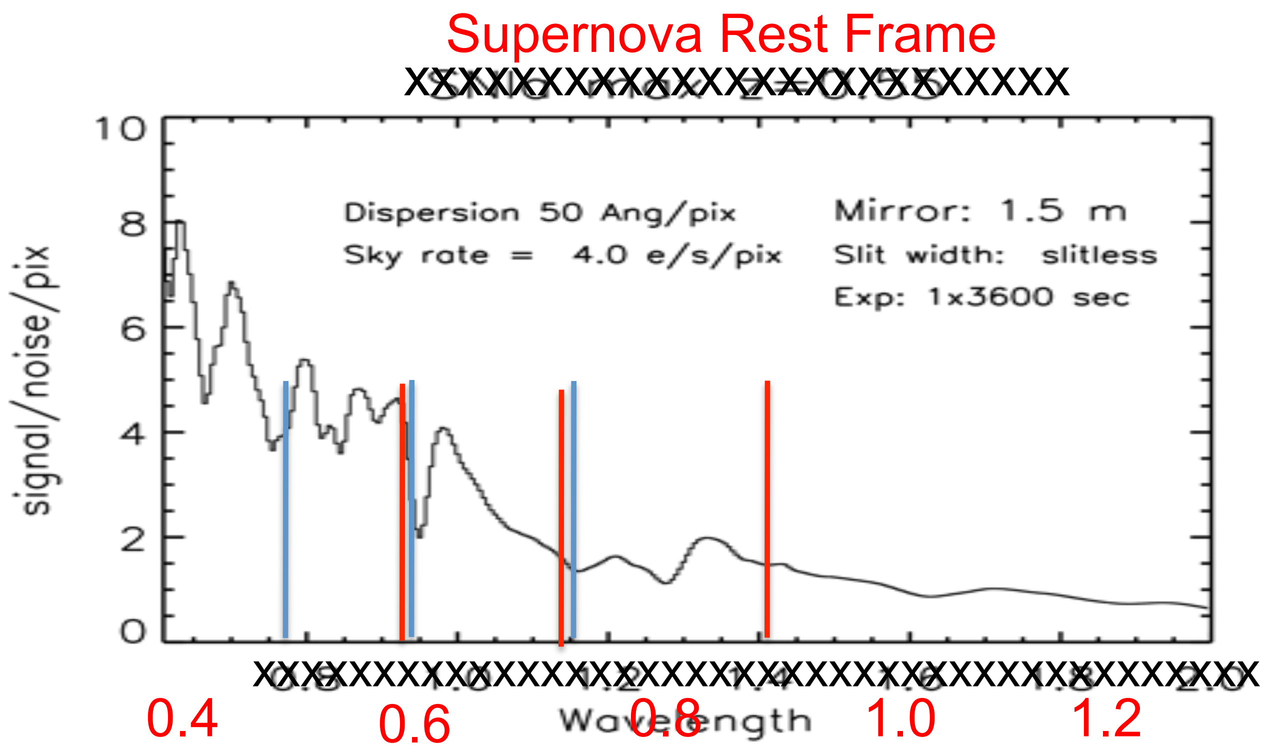
- With only three filters available, need a HUGE K correction

Supernova	Z	Bluest Filter	Rest Frame Band
SNE1	0.4	1.0 – 1.28	0.71 – 0.91
SNE2	0.8	1.0 – 1.28	0.56 – 0.71
SNE3	1.2	1.0 – 1.28	0.45 – 0.58

The Filter Bands in SNe Rest Frame -- 5 Filter Set



The Filter Bands in the SNe Rest Frame -- 3 Filter Set



Summary

- Five Filters are desireable to minimize reliance on K corrections (recall that SNAP proposed 8 or 9 filters!)
- With three filters will either have huge K corrections driving up the systematic errors or will have to restrict the SNe redshift range severely, either way lowering the Figure of Merit.

Spectroscopy

- Plan to use the slitless prism spectrometer on the filter wheel
- Use resolution R=75 (150/pixel)
- Limit spectra wavelength range 0.6 to 2.0µ
- Each of the three filter bands will correspond to 150/4.5 = 44 pixels in the dispersion direction.

Spectroscopic Exposure Times

- Use the Silicon II spectral feature at 6100Å (FWHM=160Å, FW at base=320Å) to recognize a Type 1a and to measure redshift (will use this for a simple estimate; ultimately will use other weaker lines as well)
- Want S/N=5 (for spectra coadded from the whole sequence) for the Si feature for positive ID and

  z measurement

Silicon II Spectral Feature

In Observer Frame	SNe rest Frame	Z=0.5	Z=1.0	Z=1.5
λ central	6100	9150	12200	15250
FWHM	160	240	320	400
FW at base	320	480	640	800
Å per pixel	41	61	82	102
FWHM in pixels	3.9	3.9	3.9	3.9
FW at base in pixels	7.8	7.8	7.8	7.8
S/N per pixel coadded sp*	2.1	2.1	2.1	2.1
S/N per pixel single sp**	0.7	0.7	0.7	0.7

*Signal to noise per pixel in co-added spectra to get a S/N = 5 for the Si feature. Use 6 pixels, so 5/√6 = 2.1

**Assume that S/N in a co-added spectrum (i.e.co-add all spectra in the lightcurve) is 3 times the S/N in a single spectrum

Conclusion: Need S/N per pixel = 0.7 for single spectra

Spectroscopic Exposure times to get S/N = 0.7/pixel

- Ran calculations to estimate slitless spectroscopy exposure times needed to get S/N = 0.7 per pixel at various redshifts

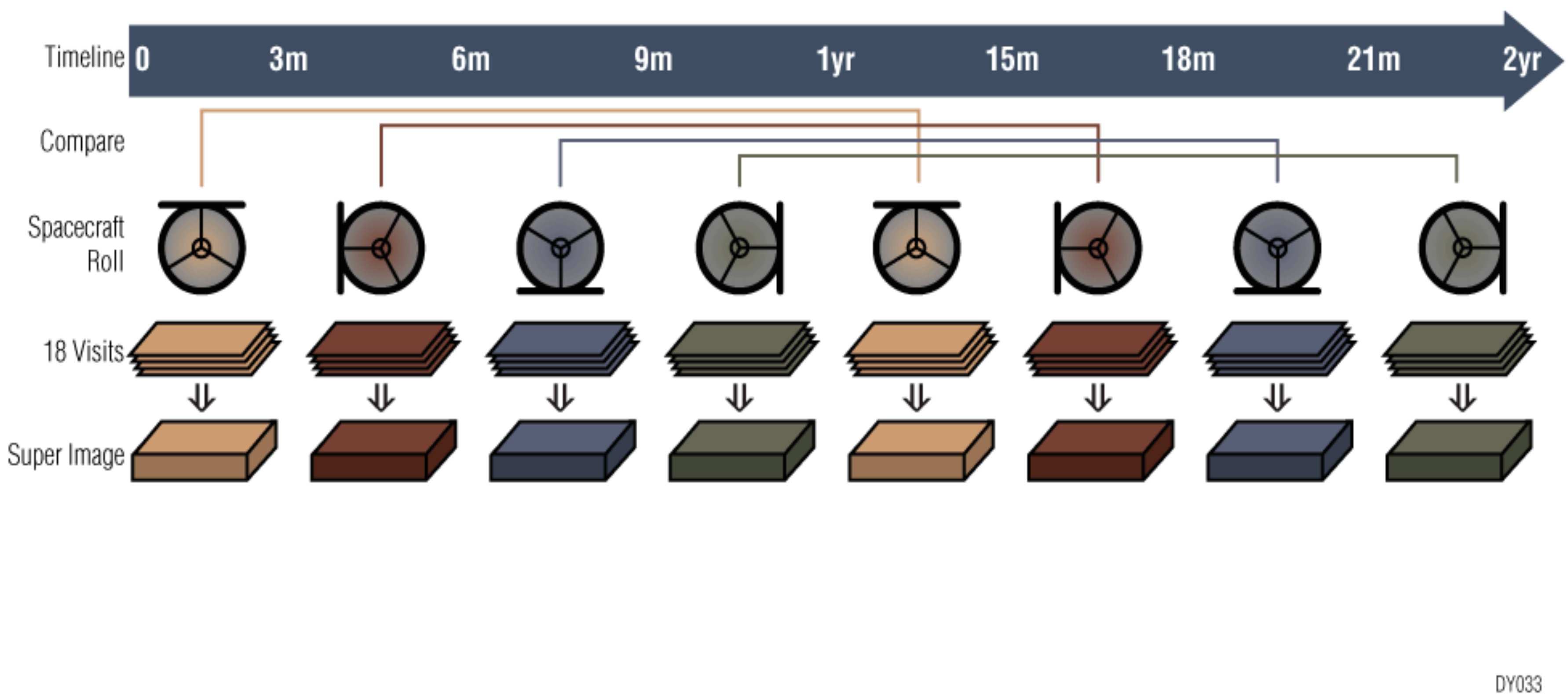
Redshift	Exp time (sec)
0.6	200
0.7	700
0.8	1300
0.9	2000
1.0	2800
1.1	4000
1.2	6400

For this calculation used Supernova fluxes from a band centered at 6100A, (the Si feature) in the supernova rest frame.

This requirement determines the Maximum redshift we can go to

Survey Areas

- We want a square area so we can continuously monitor it as we go around a corner every three month with a 90 degree turn of the detector plane



Survey Areas

- We want a square area so we can continuously monitor it as we go around a corner every three month with a 90 degree turn of the detector plane
- We are quantized by the detector array of Omega which is 4 detectors wide X 6 detectors long
- Each detector is 2K x 2K pixels 0.18”/pixel for 0.01 sq deg/detector
- For example a pattern of 2 fields long and 3 fields wide would have 12 x 12 detectors = 144 detectors or 1.44 sqare degrees.
- Another example would be an area 3 fields long x 4 fields wide: 18 x 16 detectors. The common square area is 16 x 16 = 256 detectors or 2.56 square degrees

Nearly Square Survey Areas

Pattern	Detectors	Square	Area (sq deg)	No of shots
2L x 3 W	12 x 12	12 x 12	1.44	6
3L x 4W	18 x 16	16 x 16	2.56	12
3L x 5W	18 x 20	18 x 18	3.24	15
4L x 6W	24 x 24	24 x 24	5.76	24
5L x 7W	30 x 28	28 x 28	7.84	35
5L x 8W	30 x 32	30 x 30	9.00	40
6L x 9W	36 x 36	36 x 36	12.96	54

The image plane is 6 detctors Long and 4 detectors Wide

A pattern of 2L x 3W is 6 image planes arranged 2 in the L direction and 3 in the W direction

No of shots is no of exposures in a single filter

We should stick with these patterns for best efficiency. The most efficient are the 2L x 3W, 4L x 6W, and 6L x 9W

Exposure Time Calculation

- Input parameters used in the spreadsheet
  - 1.5 m on axis telescope
  - Slitless prism spectrometer with an R = 75 (i.e.150/pixel)
  - Wavelength range entering spectrometer is 0.6 to 2.0µ
  - 24 NIR detectors with
    - plate scale = 0.18”/pix
    - read noise = 5 e
    - dark current = 0.05e/pix/sec
- Zodiacal light background from paper by Greg Aldering
  - $\log_{10} f(\lambda) = -17.755 - 0.73(\lambda - 0.61)$ ergs/cm^2/sec/Å/arcsec^2
- AB magnitudes of the supernova chosen to include 80% of the supernova at each redshift

Supernova Signal counts/sec/Filter Band

- The supernova signal in the three filters was calculated by transforming the observer frame filter bands to the supernova rest frame and evaluating the flux in these rest frame bands.

Z	Band 3	Band 4	Band 5
0.15	15.397	11.743	7.209
0.25	7.344	5.150	3.896
0.35	4.058	3.083	2.519
0.45	2.499	2.232	1.763
0.55	2.028	1.705	1.220
0.65	1.743	1.305	0.943
0.75	1.591	0.974	0.787
0.85	1.392	0.756	0.724
0.95	1.137	0.720	0.611
1.05	0.968	0.698	0.529
1.15	0.795	0.654	0.439
1.25	0.707	0.632	0.370
1.35	0.636	0.590	0.331
1.45	0.576	0.519	0.340
1.55	0.560	0.467	0.340
1.65	0.530	0.421	0.326

Imaging Exposure times

Z	Band 3	Band 4	Band 5
0.15	17.7	23.7	40.6
0.25	40.8	62.4	86.0
0.35	85.5	122.7	155.1
0.45	168.4	196.2	263.7
0.55	231.4	299.1	479.8
0.65	294.5	466.8	750.5
0.75	341.9	781.1	1039.1
0.85	427.7	1245.6	1212.7
0.95	607.8	1364.8	1668.0
1.05	812.2	1448.5	2194.2
1.15	1167.3	1634.5	3138.2
1.25	1454.9	1744.5	4373.2
1.35	1778.2	1992.2	5432.9
1.45	2148.9	2550.6	5166.4

Exposure times in each of the filter Bands for a S/N=15 in each band

Calculated exposure times as:

$t = n_{pix} [(S/N)/s]^2 (Z+D+r^2/t)$ sec

n_{pix} = no of pixels in image
S/N = 15 required signal to noise
s is SNe signal in counts/sec/band
Z is the Zodi bckgrd in cts/sec/pix
D is the dark current in cts/sec/pix
r is the read noise (assume single read here, should change with multiple exposures per point)

Measurements Errors on each Supernova

- Estimate that we need a S/N = 15 in each band to get a measurement error of 12% for each supernova
- The actual exposure times we propose to use are not as long as the times we have calculated as required to get 12 % measurement error for each supernova.
- Estimate actual measurement error as

$$\sigma_{\mathrm{meas}} = (12\ \%) \times \mathrm{Sqrt}\ (\text{time needed for } 12\%/\text{actual exp time})$$

- Assign this error for each supernova

Error Model Used

- Use the program by Eric Linder to calculate Figures of Merit
- Statistical errors i.e. errors that are reduced by 1/sqrt(N)
  - 12 to 16 % for the inherent spread with a low S/N spectrum,
  - measurement errors per supernova that varies with z bin
  - Add these in quadrature as σ_{stat}
- Systematic (only partly calibration) error 2.0 % flat in z except first bin (z<0.1).
- Add these in quadrature $\sigma_{tot} = \mathrm{sqrt}(\sigma_{stat}^2 + \sigma_{sys}^2)$

Start with a Survey limited to z < 0.8

- Suppose we want to optimize the survey to go up to z = 0.8
- To get lower lower z SNe's do a two tier search with:
  low z search up to z=0.4 with 200 sec exposures for spectra
  high z search up to z=0.8 with 1500 sec exposures for spectra
- Keep spectra to 1500 sec and 200 sec, which is the minimum needed to type and get redshift up to z = 0.8 and 0.4 resp.
- Use intrinsic supernova spread as we agreed:
  - Rest frame B band 16 %, (2% systematic error)
  - Rest frame Z band 15 %, (2% systematic error)
  - Rest frame J band 13 %, (1.5% systematic error)
  - Rest frame H band 12 %, (1.5% systematic error)

Z range	Z max	Area	Spectr exp time	Filter exp time
Low z	0.4	9.00	200	300
High z	0.8	5.76	1500	600

FoM = 40

SNe Survey for $0.4 < z < 0.8$

- To minimize K corrections limit the SNe redshift range as discussed above
- From the previous survey remove the low z tier, increase time for high z tier from 22 hours to 30 hours.
- Get FoM = 21

Systematic Errors

- The Figures of Merit depend sensitively on the systematic errors assumed. These errors depend on, among other things,
  - Photometric calibrations over the large redshift range
  - Corrections for the filter bands translating to different SNe rest frame bands (K corrections)
  - Extinction corrections
  - Malmquist bias effects etc
  - Supernova evolution
- We have simulated these errors and for the first round of calculations are using a 2% error flat in z.
- More work on this challenging issue is in progress, including correlated errors across the z bins, which may reduce (or increase??) this number

Next

- Try to go to survey strategies with somewhat higher redshifts.
- Try some alternatives with 1, 2 or 3 tiers.

One Tiered Survey

- Do a single area, the same for both imaging and spectroscopy, with a single exposure time for imaging and another exposure time for spectroscopy.

Imaging	Spectro	Area	Imaging shots	Spectro shots	Imaging Exp Time	Spectro Exp Time	Zmax	FoM
1/3	2/3	3.24	24 x 3	24	800	4800	1.1	57
1/2	1/2	3.24	24 x 3	24	1200	3600	1.0	46
2/3	1/3	3.24	24 x 3	24	1600	2400	0.9	35

Nos of SNe and Errors

- 1 tiered survey, 3.24 sq deg, 1/3 imaging, 2/3 spectroscopy

z	No	S/N	No	S/N	No	S/N	Total	σ	σ√N
0.15	5	15.89	0	0.56	0	0.56	5	0.161	0.070
0.25	15	8.68	0	0.31	0	0.31	15	0.162	0.041
0.35	30	5.24	0	0.19	0	0.19	30	0.166	0.030
0.45	50	3.43	0	0.12	0	0.12	50	0.171	0.024
0.55	74	2.39	0	0.08	0	0.08	74	0.179	0.021
0.65	98	1.76	0	0.06	0	0.06	98	0.191	0.019
0.75	122	1.35	0	0.05	0	0.05	122	0.204	0.018
0.85	151	1.07	0	0.04	0	0.04	151	0.221	0.018
0.95	174	0.87	0	0.03	0	0.03	174	0.228	0.017
1.05	192	0.72	0	0.03	0	0.03	192	0.234	0.017

No is no of supernovae, S/N is the signal to noise per pixel in a single spectrum, σ is the statistical error (measurement and intrinsic combined) for a single supernova combining errors from imaging and spectra.

Two Tiered Survey

- Do larger area for low z with short exposure times, smaller area for high z with long exposure times to even out the numbers of supernova across the redshift bins. The same areas for both imaging and spectroscopy
- Explore a range of time splits between imaging and spectroscopy

Imaging	Spectro	Low z area	High z area	Low Zmax	High Zmax	FoM
1/10	9/10	3.24	1.44	1.1	1.3	62
2/10	8/10	3.24	1.44	1.0	1.2	66
1/4	3/4	3.24	1.44	1.0	1.2	67
1/3	2/3	3.24	1.44	1.0	1.2	68
1/2	1/2	3.24	1.44	0.9	1.1	58
2/3	1/3	3.24	1.44	0.8	1.0	46

A 3 Tiered Imaging/Spectroscopy Survey

Time split 1/3 Imaging, 2/3 Spectroscopy

Z region	Area sqdeg	Spect shots	Filter shots	Spect Exptime	Filter Exptime	Zmax	FoM
Low	9.00	40	120	200	33	0.5	
Mid	3.24	15	45	2400	400	0.9	
High	1.44	6	18	4800	800	1.1	

FoM = 63

Dependence of the FoM on the Low z search area

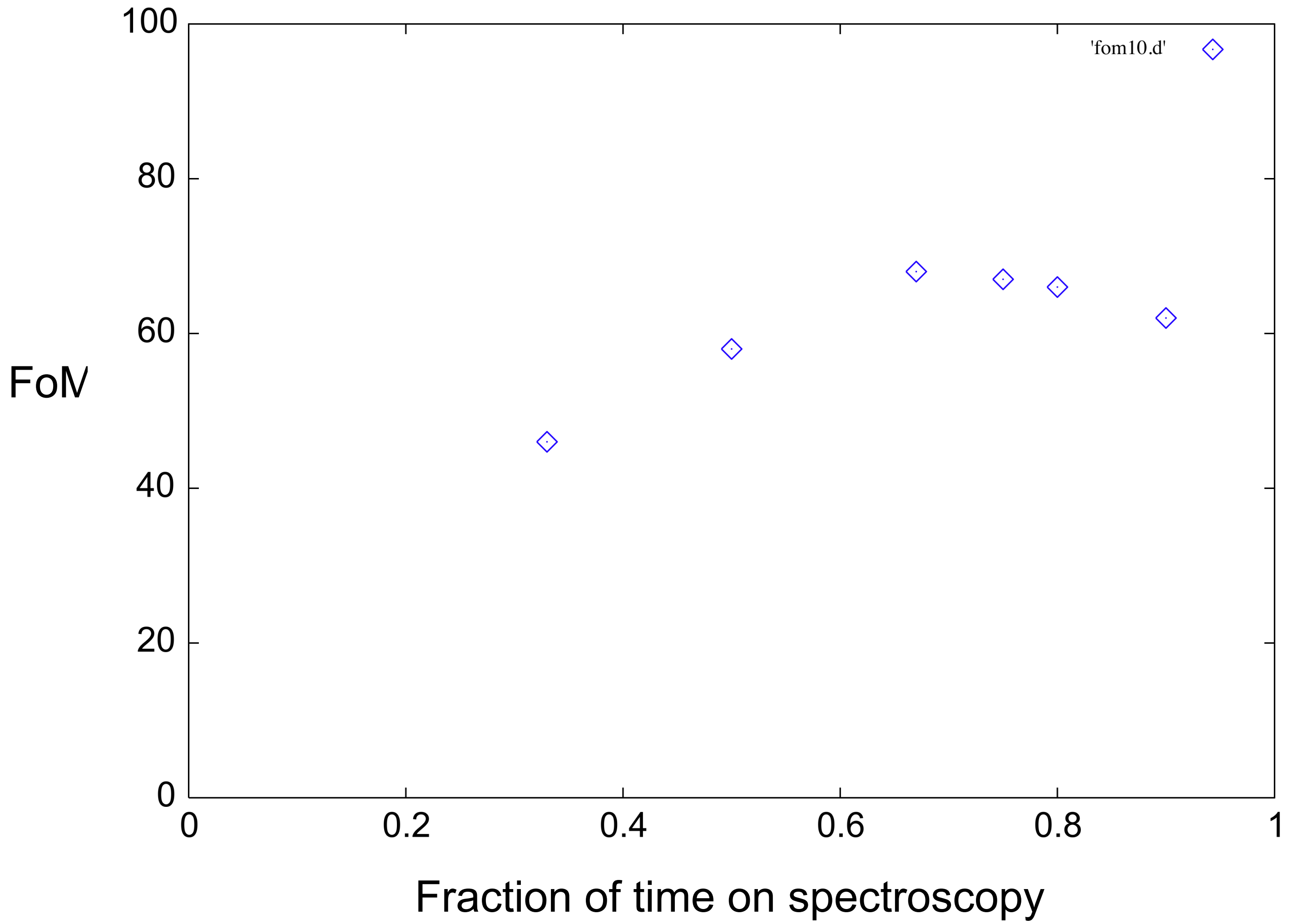
- Two tier survey, keep Hi z area constant at 1.44 sq degrees, vary the Low z area.
- Smaller area means longer exposure times
- Optimum seems to be at 3.24 sq degrees

Imaging	Spectro	Low z Area	Hi z Area	Low Zmax	Hi Zmax	FoM		
1/3	2/3	2.56	1.44	1.0	1.2	66		
1/3	2/3	3.24	1.44	1.0	1.2	68		
1/3	2/3	5.76	1.44	0.9	1.1	61		
1/3	2/3	7.84	1.44	0.8	1.0	48		

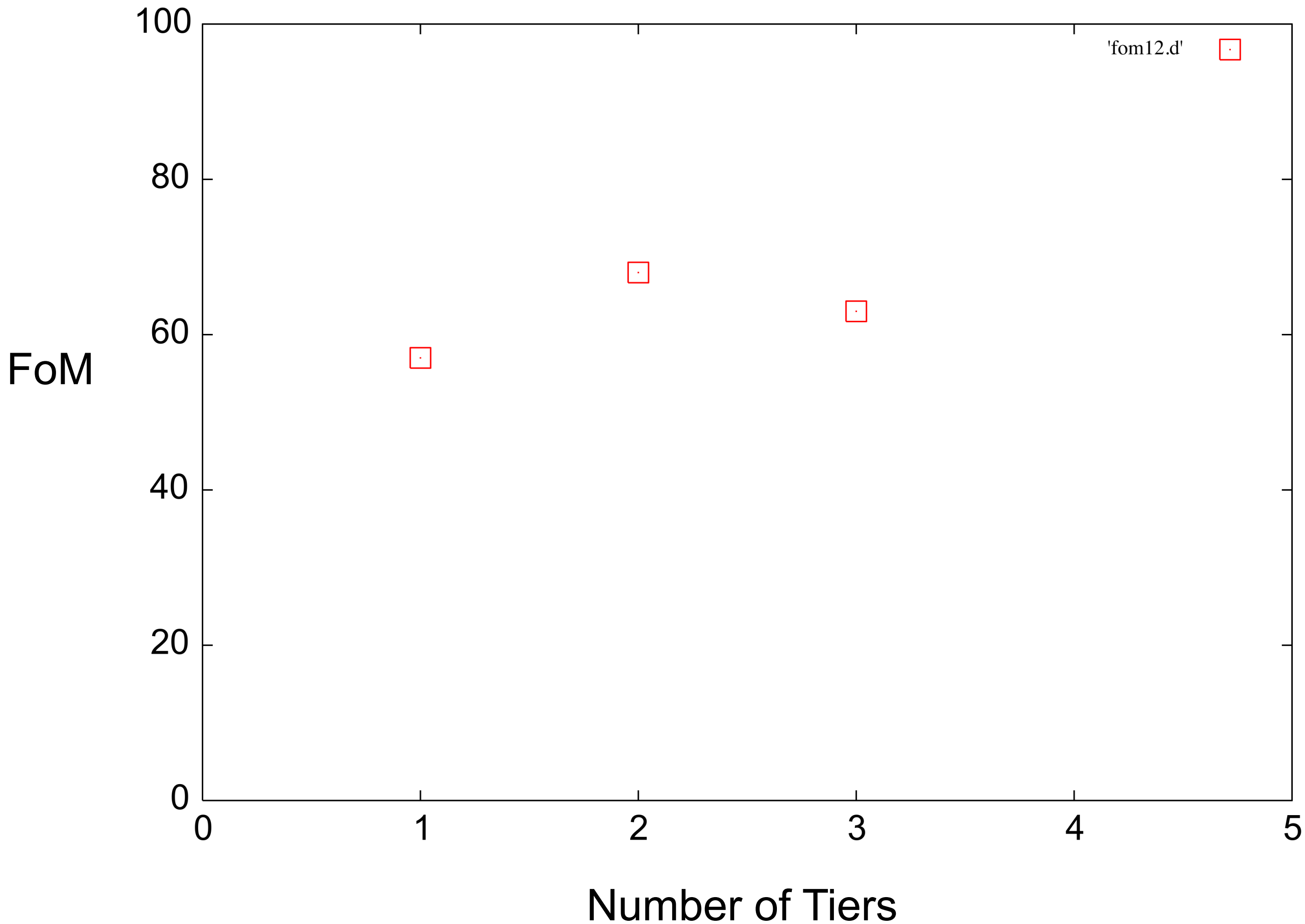
Optimizing the parameters of the Survey

- Survey parameters to optimize
  - A. Division of time between Imaging and Spectro
  - B. No of tiers
  - C. For multi tier surveys, the area of the low z survey (for the hi z survey we are pretty much locked into 1.44 sq degrees-it's the smallest square area with the Omega imager, and not enaugh time for the next larger area)
  - D. Vary filter bands used

A.Figure of Merit vs Imaging/Spect Time Split

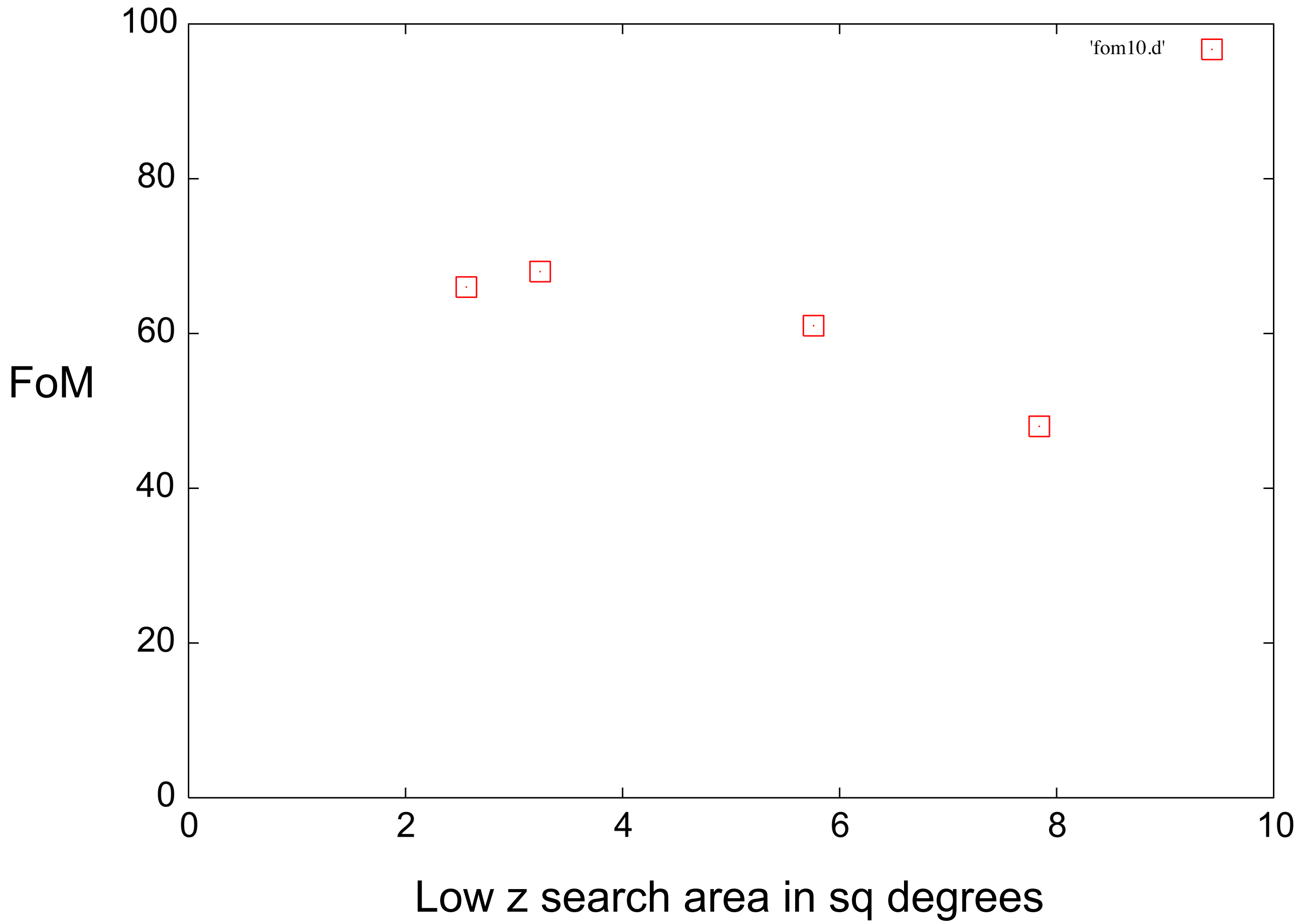


B. Dependence of FoM on no of Tiers



C. Dependence of the FoM on the Low z search area

Two tier search keeping Hi z area constant at 1.44 sq degrees



The Best Survey Parameters So Far

- Division of time between imaging and spectrometry : 1/3 imaging, 2/3 spectro
- No of tiers 2
- Survey areas 3.24 sq deg for low z
  1.44 sq deg for hi z
- Redshifts up to z = 1.2
- The best Figure of Merit is 68 for Supernova alone. Next we have to combine with BAO & WL---that may change the landscape